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by

J. S. Hay.

(Meteorological Office)

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Evaporation from a saturated rough surface into a turbulent air stream

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Summary

Wind tunnel measurements have been made of the rate of evaporation from saturated rough surfaces consisting of plaster casts in the form of rectangular ridges 0.3 cm. high or truncated cones 0.95 cm. high arrayed on a flat base of approximate dimensions 25 x 12 cm. For purposes of comparison, measurements were also made of the rate of evaporation from smooth surfaces of the same material. The vertical distribution of wind speed and of vapour concentration in the first few centimetres above the various surfaces were also studied, the former being used to confirm that the flow was aerodynamically rough or smooth according to the type of surface used and to compute the drag coefficient of the surface.

The variation of the rate of evaporation with wind speed was found to be similar, at least within a few per cent. for both smooth and rough surfaces over the range 1 to 9 m./sec. The absolute rate of evaporation from a smooth surface, however, was approximately half that from a rough surface of the same base area. Although the anticipated agreement between the drag and mass transfer coefficients in the case of a smooth surface was confirmed here, a pronounced discrepancy between the two was obtained in the case of the rough surfaces, the drag coefficient being 3 to 4 times the mass transfer coefficient. This lack of analogy between momentum and mass transfer processes over a rough surface is in keeping with a similar discrepancy between momentum and heat transfer observed elsewhere. The implied difference in mass and momentum coefficients for an array of cylinders is consistent with that observed directly for heat and momentum transfer.

Owing to the breakdown in the analogy between momentum and mass transfer near the boundary and to the fact that the vapour cloud did not extend substantially above the roughness elements, treatments of evaporation such as that developed by Calder (1949) cannot be expected to apply to the present cases.

1. Introduction

Much experimental study of evaporation from plane, free liquid surfaces has been carried out, notably by F. Pasquill (1942 and 1943), who attempted to relate evaporation to the aerodynamic conditions over the surface. He found the absolute rate of evaporation to be predicted satisfactorily by a theory due to O.G. Sutton (1943), apart from minor variations with the physical properties of the liquid. Pasquill suggested an empirical generalisation of Sutton's treatment, involving replacement of kinematic viscosity in the turbulent exchange coefficient by the appropriate molecular diffusion coefficient.

The aerodynamic conditions in Pasquill's experiments were of the so-called "aerodynamically smooth" type. In many practical problems of boundary layer

flow however, especially in the lower atmosphere, the flow is of the "aerodynamically rough" type, resistance arising from pressure forces on the roughness elements and being independent of fluid viscosity.

The work described in the present paper is an extension to rough surfaces of the work previously done on smooth surfaces. It was commenced by S.G. Crawford (unpublished) who employed a surface which was saw-tooth in form and will be referred to as type RA. Finding the rate of evaporation to be lower than anticipated, Crawford turned his attention to a surface with parallel ridges but had to discontinue the research at this point. A surface of this type, designated type RB, and also one with small truncated cones as the roughness elements, type RC, both described in detail in the following section, were used by the author. Sections of these three types of surface are shown in figure 1. The measurements of evaporation were made using sections about 300 cm.^{2} in area and in wind speeds ranging from 1 to 9 m./sec.

2. Experimental details

The wind tunnel employed was that used and described by Pasquill (1942 and 1943). For present purposes, it is sufficient to note that the working section was 4 ft. long and 30 in. square but for fuller details, the reader is referred to the original papers. The modifications described therein were not however considered necessary in the present investigation for it was anticipated that the use of rough surfaces would ensure fully turbulent flow. The tunnel was thus restored to its original form, though without the gauze. Air was drawn in from outside the building and after passing through the working section was expelled from the building. By doing so, a build-up of vapour concentration within the room housing the wind tunnel was avoided.

A number of calestone (dental plaster) casts, prepared in tufnol moulds, were laid out on the floor of the working section to form the rough surfaces. Each cast consisted of a thin rectangular base with the roughness elements arrayed on it. The first rough surface used by the author, type RB, had small parallel ridges running across the working section of the wind tunnel. The second, type RC, had truncated cones spaced regularly in rows across the working section, the rows being staggered so that each cone was mid-way between two cones in the adjacent rows. Details are as follows:-

Type of surface	Dimensions of base	Description of roughness elements
RB	25.0 x 12.5 x 0.3 cm.	Ridges 0.3 cm. high, 0.15 cm. wide, spaced 2.5 cm. apart.
RC	23.9 x 12.1 x 0.4 cm.	Cones 0.95 cm. high, 0.2 cm. in diameter at top and 0.6 cm. at bottom, spaced 2 cm. apart in rows 1 cm. apart.

The evaporation plates were similar casts but with thinner bases attached to thin glass sheets of the same area, the total thickness being the same as that of an ordinary cast. The thinner bases meant an appreciable saving of liquid required for saturation. To prevent leakage, the edges of the plates were painted with shellac. The evaporation plate was positioned close to the downwind end of the working section with seven rows of ordinary casts, three in each row, upwind of it, one row downwind and a cast on either side. This ensured as deep a layer as possible of fully developed flow characteristic of the surface over the evaporation plate.

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With the rough casts removed, experiments were also carried out with smooth evaporation plates, recessed into the floor of the working section at the position normally occupied by the rough evaporation plates. They were prepared in the same way and were equal in area to the bases of the rough plates. They will thus be referred to as smooth type SB and SC plates. A few observations were made using filter papers, almost equal in area to the type B plates, placed on a sheet of glass recessed into the floor at the same position.

The first evaporation plates were made of plaster of paris as they appeared to be more absorbent and so presumably more porous than calestone ones. Later it was found that absorbency varied considerably with the consistency of the mixture before it set and that calestone casts could be made just as absorbent as plaster of paris ones. Calestone was then preferred for it was stronger and the rather watery mixture took longer to set, allowing more time for pouring into the mould. Similar results were obtained with both materials and no further distinction need be made. The significance of absorbency will be discussed in Section 4.

Bromobenzene was chiefly employed as the evaporating liquid. The rate of evaporation E was determined gravimetrically using a balance positioned close to the working section. The balance scale was graduated in divisions of 0.1 g. and the readings estimated to 0.01 g. but tests showed it to be accurate to only 0.03 g. Other tests were carried out daily to estimate the loss of vapour during transfer of plate between balance and tunnel and a correction applied. Taking into account the reproducibility of the weighings and of the transfer correction, the weights of liquid evaporated during a single exposure in the tunnel are considered to be accurate to 0.1 g. As the exposures were long enough for 2 g. or more to be evaporated the errors in the rates of evaporation arising from the weighing measurements were within about 5 per cent.

The temperature T_a of the free air stream, indicated by a thermometer projecting through the roof of the working section, was noted at intervals and the mean during each exposure obtained. Practical difficulties precluded the direct measurement of surface temperature T_s. Subsidiary experiments with evaporation plates having several thermocouple junctions embedded in them were however carried out to determine the extent of surface cooling during evaporation.

The free air speed V during the period of exposure was measured by a Sheppard (1940) type anemometer positioned at the downwind end of the working section, and a little to one side, with its cups high above the floor, about 21 in., to avoid interference with the flow over the evaporation plate. The anemometer readings were related to the free air speed immediately above the plate by calibrating it against a small pitot-static tube, external diameter 0.3 cm. whose orifice was about 4 in. above one of the smooth plates. Observation showed that the wind speed distribution across the working section varied slightly with the ventilation conditions. Separate calibrations were accordingly carried out in the two sets of conditions employed.

Besides the main evaporation experiments, observations were made of the wind speed and vapour concentration profiles in the first few centimetres above the various surfaces. In the former case, the wind speed u at a number of heights and the corresponding free air speed V were measured by the small pitot-static tube and anemometer respectively. In the latter case, vapour samples were taken over type SB and RC plates saturated with methyl acetoacetate (MAA). The choice of MAA was governed by the fact that facilities for estimating the quantities of vapour absorbed, and hence the concentrations, by chemical methods were readily available.

3. Wind speed profiles

Two series of measurements, mostly in a free air stream of 5 m./sec., were made over each surface, with an interval of about two years between each. The measurements were first repeated over surface RC in an endeavour to find some

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explanation for an increase in the rate of evaporation which is discussed in the following section. When a change in this profile became apparent, the measurements were repeated over the other surfaces to see how well the previous results could be reproduced.

Within the boundary layer, the wind speed was not constant across the mouth of the pitot-static tube so that each value of u was appropriate not to the centre of the orifice but to a point slightly above it. To take this into account, a height correction of 0.048 cm. was applied, derived from a formula due to Young and Mass (1937). Corrected heights, referred to the base of the roughness elements, will be denoted by z. Fluctuations in the flow through the tunnel, due to gusts outside the building, may at times have given rise to errors of about 5 per cent in the values of u.

Over surface RB, the measurements in both series were made with the pitot-static tube in two positions, first with the orifice directly above a ridge and again mid-way between two ridges, at distances of 96.25 and 95 cm. respectively from the upwind edge of the surface. The wind speed ratios $\frac{u}{V}$ obtained in the second series of measurements have been plotted against $\log_{10} 10z$ in figure 2. The distribution obtained in the first series was similar in shape. It will be seen that close to the surface the profile varies with position, the wind speed at a given height being apparently greater between the ridges than above them, contrary to what might be expected. No great reliance however can be placed on the measurements in this region for the static holes were some 1.9 cm. behind the orifice of the tube. The Chattock-Fry manometer to which the pitot-static tube was connected thus recorded the difference between the dynamic plus static pressures at one point and the static pressure at another point. At the greater heights, above about 1.6 cm., the profile is clearly independent of position, indicating that the pitot-static tube is not subject to local effects and that the flow is characteristic of the surface.

Over surface RC, wind speeds in the first series were measured with the pitot-static tube in four different positions relative to the cones, the orifice being 92 cm. from the upwind edge of the surface in each case. The wind speed ratios did not appear to be dependent on position for heights above the top of the cones. The second series of measurements, with the tube employed in one position only, gave a similar distribution of wind speed ratios, shown in figure 2.

Laboratory studies (Nikuradse (1933) and Schlichting (1936)) have established that the wind speed distribution in aerodynamically rough flow, for which the parameter $\frac{u_* z_o}{\nu} > 2.5$, may be written in the form

$$\frac{u}{u_*} = 5.75 \log_{10} \frac{z}{z_o} \qquad (1)$$

where z_o is the roughness parameter of the surface, ν is the kinematic viscosity of the fluid and $u_* = \sqrt{\tau_o / \rho}$ is the shearing stress velocity, τ_o being the shear stress per unit area and ρ the fluid density. The present results indicate in both cases a linear variation of $\frac{u}{V}$ with $\log_{10} 10z$, for heights above that at which local variations in flow die out. Thus, by deriving the lines of best fit, two of which are shown by full lines in figure 2, by means of the method of least squares and comparing with equation (1), appropriate values of z_o, u_* and $\frac{u_* z_o}{\nu}$ may be readily deduced*. The figures given in table 1 were obtained with V = 5 m./sec. and ν = 0.140 cm.^{2} sec. /Table

* It may be recalled that Schlichting's measurements were made in the boundary layers developing over a number of flat plates covered with different types of roughness element. Denoting the distance from the leading edge of the plate to the point at which the measurements were made by x, equation (1) was verified explicitly for the range of conditions $2.6 \times 10^3 \leq \frac{x}{z_o} \leq 3.1 \times 10^5$. Although the range of $\frac{x}{z_o}$ 272 to 406, covered by the experiments reported here lay outside these limits, it was assumed that equation (1) was still valid. It certainly appeared to be of the correct functional form.

Table 1. Values of z_o, u_* and $\frac{u_* z_o}{\nu}$

	Smooth Surface		Surface RB		Surface RC	
	Series 1	Series 2	Series 1	Series 2	Series 1	Series 2
z_o cm.	-	-	0.247	0.235	0.266	0.338
u_* cm./sec.	22.7	23.1	63.6	64.8	61.7	69.6
$\frac{u_* z_o}{\nu}$	-	-	112	109	117	168

From the values of $\frac{u_* z_o}{\nu}$, it is quite obvious that the flow was aerodynamically rough in each case. The z_o value for surface RB derived from series 1 is in good agreement with that from series 2 but for surface RC there is a marked difference, z_o having increased in value by about 27 per cent from series 1 to series 2. Statistical analysis of the data showed that the values were accurate to about 15 per cent so the difference is significant. The reason for this is not clear.

Little reference has been made to the lower parts of the profiles for these are dependent on position and are not representative of the complete surface. In working with rough surfaces, it is frequently necessary to introduce a zero-plane displacement, a datum level a little way above the base of the roughness elements, above which active turbulent exchange commences. From the linearity of the profiles, this does not appear to be necessary with either of these rough surfaces.

Two series of measurements over a type SB plate were also made, the mouth of the pitot-static tube being 97.5 and 8.5 cm. from the upwind edges of the smooth surface and plate respectively. The distribution of wind speed ratios was similar for both series, that obtained in series 2 being shown in figure 2.

An approximately linear variation of $\frac{u}{V}$ with $\log_{10} 10z$ is evident at the greater and lower heights. An unexpected feature however is the change in slope, at about 0.9 cm., which may well be associated with a very slight difference in the natures of the plate and surrounding floor. During evaporation, the major part of the vapour cloud over the plate lies beneath this level so main interest centres on the lower section of the profile. The line of best fit relating $\frac{u}{V}$ and $\log_{10} 10z$ in the interval 0.3 to 0.8 cm. was determined for both series of observations, the appropriate one being shown by the full line in figure 2.

As the plate has been assumed to be smooth it should be possible to express the wind speed distribution, over this interval at least, in the familiar form

$$\frac{u}{u_*} = 5.5 + 5.75 \log_{10} \frac{u_* z}{\nu} \qquad (2)$$

where the various symbols are as already defined. To test this, the equation was solved using the wind speed derived from the lines of best fit for the logarithmic mean height of the above interval, taking V = 5 m./sec. The resulting values of u_* are included in table 1. With these values equation (2) was then employed to calculate wind speeds at the other heights. These were found to be, on the average, within about 1 per cent. of the observed speeds corrected slightly for deviations of V from 5 m./sec. In a few instances, the

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discrepancy was a little over 2 per cent. Applying equation (1) to both sets of observations and deriving values of z_o and $\frac{u_* z_o}{\nu}$, the greater value of the latter was found to be 0.71. It may be concluded then that the flow in the vicinity of the plate approximated closely to aerodynamically smooth flow.*

Some measurements in free air speeds of 3 and 7 m./sec. over each type of surface showed no systematic variation in wind speed ratios so the profiles are independent of speed, over this range at least. Comparative measurements over dry and saturated plates also showed the profiles to be unaffected by the steep temperature gradient established close to the surface during evaporation.

4. Absolute rate of evaporation in saturated conditions

Experimental studies of the drying of a saturated solid (see for example Sherwood (1936) and Calder (1938)) have shown that the rate of drying is initially independent of time and of liquid content ("constant rate period") but subsequently decreases ("falling rate period") as the content falls below some critical value. As the aim of the present investigation was to measure the rate of evaporation as a function of wind speed and length of surface, and to examine the results in terms of treatments of turbulent exchange over a rough surface, it was clear that it could be pursued most profitably in the so-called "constant rate period". It was thus necessary initially to establish the limits of liquid content over which the constancy could be assumed for the various plates used here.

The form of the drying curve for each type of plate was studied in an air stream of 5 m./sec. After soaking the evaporation plate with bromobenzene and draining off excess liquid, it was weighed and exposed in the wind tunnel. The weighing was repeated periodically and the mean rate of evaporation E g./min. and liquid content Q g. during each exposure determined. Following Pasquill (1942 and 1943), the observations were first reduced to the form $\frac{E}{p_a}$ g./min. mm. Hg., where p_a is the saturation vapour pressure at the temperature T_a of the free air stream. These values were then increased by 7 per cent to relate the rate of evaporation to the temperature T_s of the evaporating surface which was lower than T_a, since the latent heat of vaporisation was drawn from the plate. This correction was obtained from the subsidiary experiments previously referred to, which showed that T_s fell rapidly when evaporation commenced but after 2 minutes or so it steadied and thereafter the temperature difference $T_a - T_s$ changed little. In temperatures ranging from 40 to 58°F., the difference varied unsystematically from 1 to 2.5°F., the ratio $\frac{p_a}{p_s}$ where p_s is the saturation vapour pressure at temperature T_s, varying from 1.04 to 1.10. The average ratio was 1.07 so the temperature correction was taken to be 7 per cent. It appeared to be independent of air speed from 2 to 7 m./sec. The vapour pressure data used were those quoted by Pasquill. Small corrections for deviations of air speed from 5 m./sec. were applied using the law $\frac{E}{p_s} \propto V^a$ discussed in the following section, a varying with the type of surface.

Some of the results obtained are given in figure 3 where, to facilitate comparison, values $\frac{E}{p_s}$ have been plotted against percentage saturation $\frac{100\,Q}{Q_o}$, Q_o being the maximum amount of liquid absorbed. It will be seen that there are two distinct régimes, the first characterised by a slow decrease in $\frac{E}{p_s}$ which might

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* On fitting a power law to the observations, it may be noted that the indices obtained were 0.132 and 0.141 for series 1 and 2 respectively, in good agreement with the well known $\frac{1}{7}$ value for a smooth surface.

be regarded as approximating to a "constant rate period". The slight departure from true constancy had however to be borne in mind in subsequent work. It was probably due to the underlying liquid requiring a finite time to diffuse through the plaster to replace that which had evaporated. At the lower liquid contents we have the familiar "falling rate period", probably associated with a progressive downwind drying out of the plate. The change from one régime to the other takes place at about 40 per cent. saturation in each case.

A comparison of results from the various plates is not without interest. To eliminate the effects of varying diffusive properties of plaster, the comparison must be effected in saturated conditions. Appropriate values of $\frac{E}{p_s}$ were derived by inserting Q_o values in the regression equations of $\frac{E}{p_s}$ on Q obtained from the data at the higher liquid contents, where the variation is approximately linear. They are given in table 2. Appropriate equations are represented by the full lines in figure 3, the remainder of the curves being drawn by eye. Two series of data were obtained with type SB, RB and RC plates at times corresponding approximately to those of the wind speed profiles. The two results with the SB plates were almost identical, so only one has been quoted.

Table 2. Values of $\frac{E}{p_s}$ in saturated conditions

Type of plate	Area of plate cm^2	Series	Q_o g.	$\frac{E}{p_s}$ g./min. mm. Hg.	$\frac{E \text{ rough}}{E \text{ smooth}}$
Filter paper	306	1	8	0.197 (±0.005)*	
SB	312	2	47	0.203 (±0.003)	
SC	289	1	45	0.188 (±0.006)	
RB	312	1	61	0.357 (±0.016)	1.76
RB	312	2	47	0.373 (±0.009)	1.84
RC	289	1	63	0.404 (±0.012)	2.15
RC	289	2	73	0.447 (±0.010)	2.38

* Standard error

The first feature to be noted from table 2 is that similar rates of evaporation are obtained from filter papers and smooth plaster plates, bearing in mind the differences in area. This had been observed earlier by Crawford and was taken to justify the use of plaster casts in this work. Secondly, the rate of evaporation has been enhanced by the roughening of the surface, the effect being greater with the RC surface. Crawford, with his type RA surface, found the rate of evaporation to be increased by a factor of 1.66. Thirdly, the rate of evaporation from the rough plates increased from series 1 to series 2, by a significant amount in the case of the RC surface. Various explanations for this were investigated but all had to be rejected, with the exception of a possible change in flow characteristics. When the wind profile measurements were repeated the surface roughness parameter z_o was in fact observed to have increased, as noted in the previous section, and it seems quite likely that this was associated with the increased value of $\frac{E}{p_s}$.

To demonstrate that the results given in table 2 were independent of the diffusive properties of the plaster, some data were obtained with a type RC plate of very low absorbency, and presumably low porosity. Defining absorbency as the maximum weight of bromobenzene absorbed per gram of plaster, the actual figure was 0.15, much below the range 0.55 to 0.95 covered by the other plates used in the investigation. A graph of $\frac{E}{p_s}$ against Q showed that the "falling rate period" extended up to the saturation level. At saturation however, $\frac{E}{p_s}$ was about 0.440 g./min. mm. Hg., agreeing well with the series 2 figure quoted for the RC plate in table 2.

5. Variation of the rate of evaporation with wind speed and downwind length of saturated surface

The variation with wind speed of the rate of evaporation from each type of plate was studied over the range 1 to about 9 m./sec. To minimise the effects of varying liquid content Q, the latter was maintained within certain limits and on the average was about 10 g. below the saturated value. It is estimated that variations in $\frac{E}{p_s}$ on this account were within 4 per cent. The measurements were made at about the time of the first series of wind profile observations.

To avoid the difficulty of handling longer plates, the effect of increasing the downwind length x_o of saturated surface was studied by placing one, two and then three saturated plates immediately upwind of the evaporation plate. Measurements were made with the latter alone, from which saturation values of $\frac{E}{p_s}$ from various sections of plates up to four times the normal length were inferred, and hence the total values by addition. Data were also obtained with plates on half the normal length. The measurements were restricted to the two rough surfaces and were made in an air stream of 5 m./sec., at about the time of the second series of wind profile observations.

Values of $\frac{E}{p_s}$ have been plotted against V and x_o in figures 4 and 5 respectively, the figures including the best fitting curves. Log-log plots of the data had been found to be linear so that the results could be expressed in the form $\frac{E}{p_s} \propto V^a x_o^b$. Values of the indices are given in table 3.

Table 3. Values of indices a and b

Type of surface	a	b
SC	0.782 ($\pm$0.014)*	-
RB	0.823 ($\pm$0.013)	0.940 ($\pm$0.004)
RC	0.762 ($\pm$0.009)	0.917 ($\pm$0.007)

* Standard error

The overall variation in a is about 8 per cent. so the rate of evaporation varies with wind speed in much the same manner for both rough and smooth surfaces. The standard errors do suggest however that the value of a for the RB surface may be significantly higher than the others. Similarly the values of b for the two rough surfaces only differ by about 2.5 per cent but the difference may again be significant.

As has already been indicated, the evaporation plates were never fully saturated during the determination of a. There is no reason to suppose however that values differing substantially from those quoted would have been obtained with the plates fully saturated at all times for the liquid deficiency, and hence the difference between observed values of $\frac{E}{p_s}$ and those obtaining at saturation, did not vary systematically with wind speed.

For consistency, the values of $\frac{E}{p_s}$ indicated by the curves in figure 4 at V = 5 m./sec. and in figure 5 at appropriate values of x_o should be comparable with those tabulated in the previous section. In the case of the RC plate, the value from figure 4 is about 9 per cent low, rather more than might reasonably be expected. The fact that the plate was never fully saturated would account for about half of the discrepancy but the explanation of the remainder is not clear.

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6. The analogy between momentum and mass transfer

It will be of interest to consider the results in terms of the analogy between momentum and mass transfer similar to the Reynolds analogy between momentum and heat transfer. The drag coefficient f is conventionally defined by*

$$\frac{f}{2} = \frac{\tau_o}{\rho V^2} = \frac{u_*^2}{V^2}$$

Corresponding to $\frac{f}{2}$ we have the mass transfer coefficient m defined by

$$m = \frac{E}{\chi_s V} = \frac{E}{p_s} \frac{RT_s}{MV}$$

where χ_s is the vapour concentration at the surface, M the molecular weight of the vapour, R the universal gas constant and T_s the absolute temperature of the surface. The value of $\frac{E}{p_s}$ here refers to unit area. In view of the different stages of development of the momentum and vapour boundary layers, we perhaps cannot expect equality of the coefficients. We may anticipate however that the effect of introducing the roughness elements would be shown by a similar variation in the coefficients. Values of $\frac{f}{2}$ and m derived from the figures in tables 1 and 2, after converting all units to the c.g.s. system are given in table 4, V being taken as 500 cm./sec. and T_s as 283°A. for all three surfaces. The type SB and SC plates were found to give identical values of m.

Table 4. Values of $\frac{f}{2}$ and m

	$\frac{f}{2}$			m		
Type of surface	Smooth	RB	RC	Smooth	RB	RC
Series 1 observations	0.00206	0.01618	0.01523	0.00243	0.00428	0.00523
" 2 "	0.00213	0.01681	0.01937	0.00243	0.00447	0.00578

It will be seen that the values of $\frac{f}{2}$ and m for the smooth plates are in fair agreement, but not for the rough plates. Furthermore, while the roughness elements have produced about an eightfold increase in $\frac{f}{2}$, m has only increased by a factor of about two. This is similar to the discrepancy between drag and heat transfer coefficients observed by W.F. Cope (1941) in experiments on the heating and cooling of water flowing through smooth and rough pipes. In his case, the drag coefficient of the roughest pipe was as much as six times that from a smooth pipe while the heat transfer coefficient was rather less than twice as much.

A circular cylinder placed transverse to the airstream may be regarded as an elementary form of roughness element. It is of interest then to refer to results obtained with such a body. A.P. Colburn (1933) has shown that there is in fact no analogy between momentum and heat transfer in this case, the drag coefficient being greater than the heat transfer coefficient. At low Reynolds numbers, when the flow is streamline, the difference is quite small, possibly associated with the difference in the molecular constants, kinematic viscosity

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* There is no significance in the definition of $\frac{\tau_o}{\rho V^2}$ by $\frac{f}{2}$ instead of f, other than the fact that it is customary to do so.

and thermal diffusivity. With turbulent flow however, the difference increases with increasing Reynolds number, the factor becoming as large as 100 approximately. Colburn concluded that the transfer of heat to and from the cylinder was associated with skin friction alone, the process being independent of the form drag, the major component of the total resistance of a cylinder. The same conclusion must apply to the transfer of vapour from a cylindrical surface for T.H. Chilton and A.P. Colburn (1934) and R.W. Powell (1940) found good agreement between mass and heat transfer coefficients.

Results quoted for a cylinder, or rather a bank of cylinders, may be compared in a general way with those obtained with a type RC plate, assuming the cones on the latter to be equivalent to small vertical cylinders of diameter 0.4 cm. Since the values of $\frac{f}{2}$ and m are in reasonable agreement for a smooth plate, and presumably also for the smooth interspaces of a rough surface, the discrepancy in the coefficients for a RC plate will arise mainly from the contributions of the cylinders. The present results suggest therefore that for such an assembly of cylinders, the ratio $\frac{f}{2m}$ will exceed 3. From the dimensions of the plate and the wind speed distribution in the vicinity of the cylinders, the appropriate Reynolds number will be about 400. At this Reynolds number, Chilton and Colburn's results give $\frac{f}{2m}$ equal to 11 which is reasonably consistent with the value estimated from the evaporation plate results.*

7. Theoretical considerations

K.L. Calder (1949) considered the problem of evaporation from a saturated strip of rough surface of infinite extent acrosswind and of finite length downwind. He developed expressions for the rate of evaporation E per unit width acrosswind and for the distribution of vapour concentration χ above and downwind of the strip, these being in terms of parameters deducible from the wind speed profiles and the constant, boundary value of concentration χ_o. From the nature of a rough surface, it is not clear what particular level constitutes the boundary, so that the appropriate value of χ_o is largely a matter of speculation. To avoid making any suppositions however, Calder suggested that χ_o might be obtained from the expression for χ and a measured value of concentration at one level. This could then be substituted in the expression for E and the rate of evaporation calculated.

To test this suggestion, measurements were made of the rate of evaporation of methyl acetoacetate and of the corresponding vapour concentrations at a height of 0.6 cm. above a type SB plate and at nine heights ranging from 0.6 to 3.4 cm. above a type RC plate, the vapour samples being taken close to the downwind edges of the plate. In the former case the value of $\frac{E}{p_s}$ computed in the above manner using the modified forms of Sutton's formulae (Pasquill 1942 and 1943) was 1.3 times the observed value. As the formula for the rate of evaporation had already been verified independently, it was assumed that this

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* The Chilton and Colburn results are expressed in the form of a mass transfer factor which, for the present case of a liquid with saturation vapour pressure small compared with atmospheric pressure, is equivalent to our mass transfer coefficient multiplied by $(\frac{\nu}{D})^{2/3}$ where D is the molecular diffusion coefficient. Allowance has been made for this in the above discussion.

agreement demonstrated the sampling technique to be reasonably accurate. In the rough surface case, the computed values of $\frac{E}{p_s}$ varied systematically from 1.3 to 0.2 times the observed value according as the height of measurement of χ varied from 0.6 to 3.2 cm. In this instance then, the observed vertical distribution of vapour is quite different from that deduced from Calder's theory.

Since the measurements showed that most of the vapour lay below 1.6 cm. and as the logarithmic wind speed profile only obtained above 1 cm., the disagreement is not perhaps surprising. It may be recalled that the underlying basis of Calder's treatment is firstly the assumption of equality of the eddy diffusivities of momentum and mass and secondly the calculation of the former diffusivity from the logarithmic relation for the wind profile over a surface. From the lack of analogy between momentum and mass transfer demonstrated in the previous section and the fact that the vapour cloud scarcely rose above the roughness elements into the region of logarithmic wind profile, these assumptions are obviously not applicable to the small surfaces used in these wind tunnel tests. The theory is more likely to apply to areas over which the vapour cloud is considerably deeper than the heights of the roughness elements. This is borne out in an examination by Calder of vapour concentrations observed over a strip of short grassland sprinkled with aniline. The grass was less than 1 in. high while the vapour cloud was at least 2 ft. deep at each of the sampling positions. Relating all observed and calculated concentrations to those at one level, to avoid the difficulties regarding χ_o, good agreement between observed and calculated ratios was obtained.

8. Acknowledgements

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References

Calder, K.L.	1938	Porton Report, No. 2036.
Calder, K.L.	1949	Quart.J.Mech.App.Math., 2,153.
Chilton, T.H. and Colburn, A.P.	1934	Ind.Eng.Chem., 26,1183.
Colburn, A.P.	1933	Trans.Am.Inst.Chem.Engrs., 29,174.
Cope, W.F.	1941	Proc.Inst.Mech.Eng., 145,99.
Nikuradse, J.	1933	Ver.Deutsch.Ing.Forsch., No.361.
Pasquill, F.	1942	Porton Report, No.2335.
Pasquill, F.	1943	Proc.Roy.Soc., A,182, 75.
Powell, R.W.	1940	Trans.Inst.Chem.Engrs., 18,36.
Schlichting, H.	1936	Ingen.Arch., 7, 1.
Sheppard, P.A.	1940	J.Sci.Instrum., 17,218.
Sherwood, T.K.	1936	Trans.Am.Inst.Chem.Engrs., 32,150.
Sutton, O.G.	1934	Proc.Roy.Soc., A, 146, 701.
Young, A.D. and Mass, J.N.	1937	Reports and Memoranda of the Aeronautical Research Committee No. 1770.

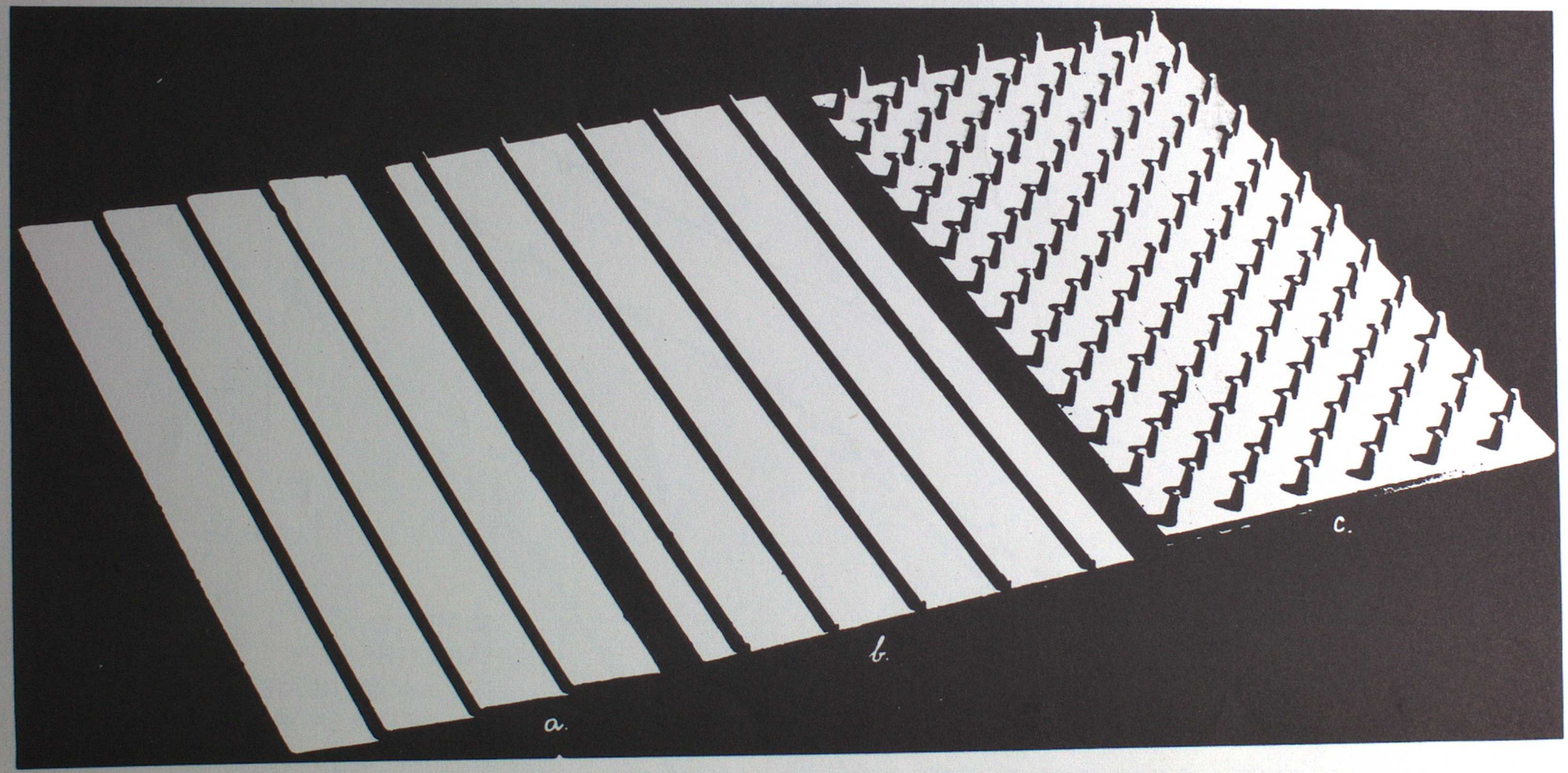

FIGURE 1. THE ROUGH SURFACES

(a) RA (b) RB (c) RC

M.R.P. 973

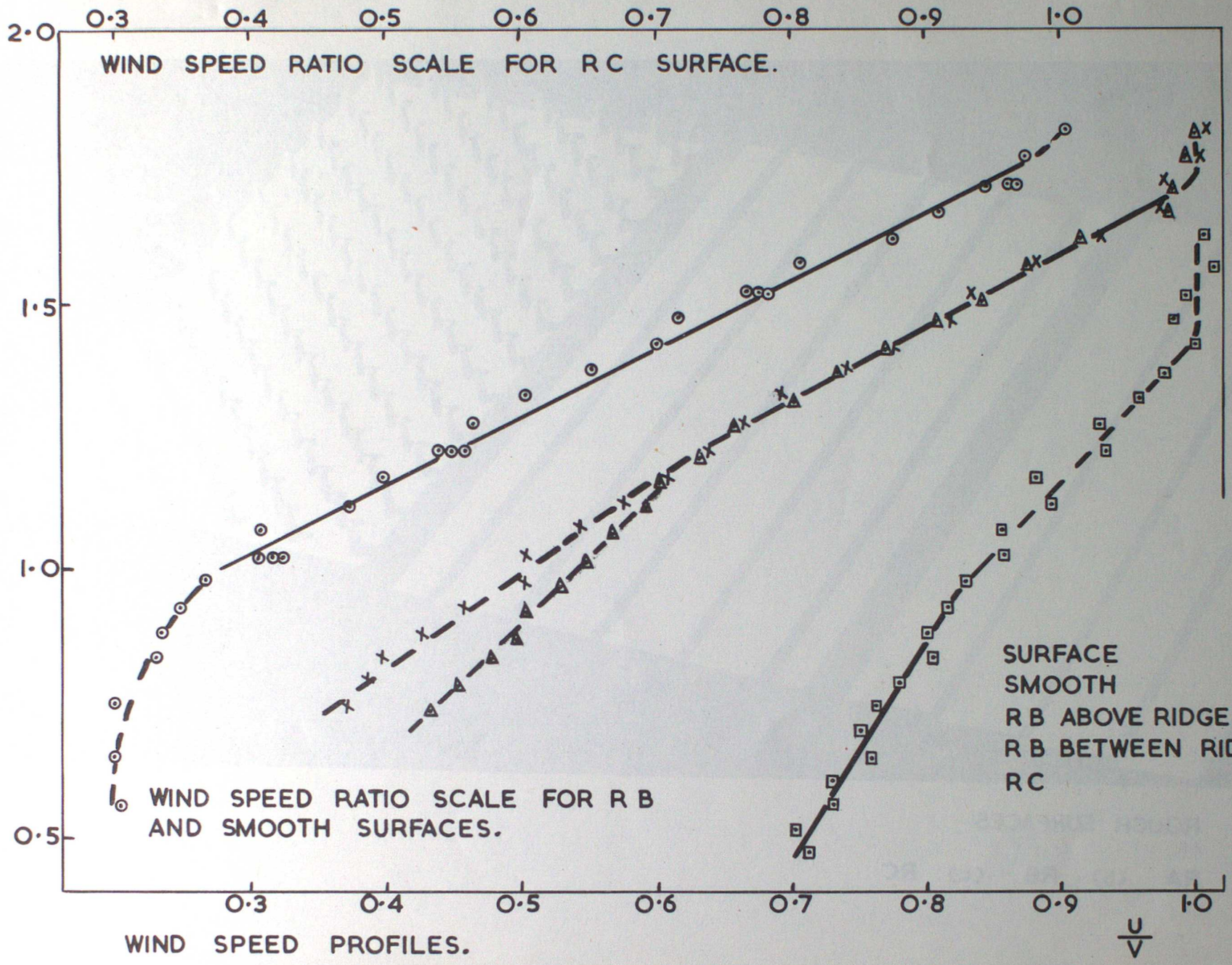

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FIG.2. WIND SPEED PROFILES.

M.R.P. 973

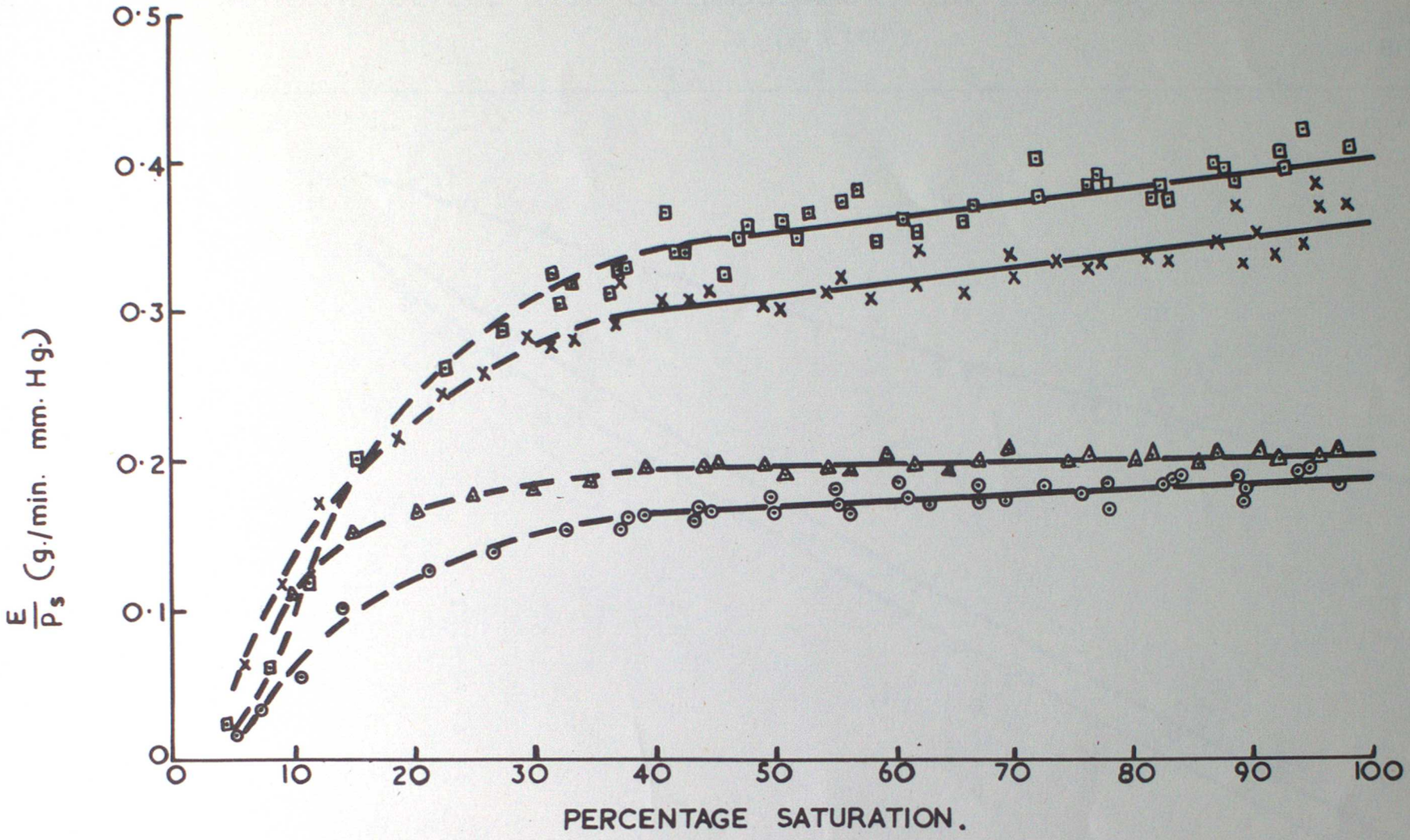

FIG. 3. THE DRYING CURVES.

PLATE	SYMBOL
SB	△
SC	⊙
RB	×
RC	⊡

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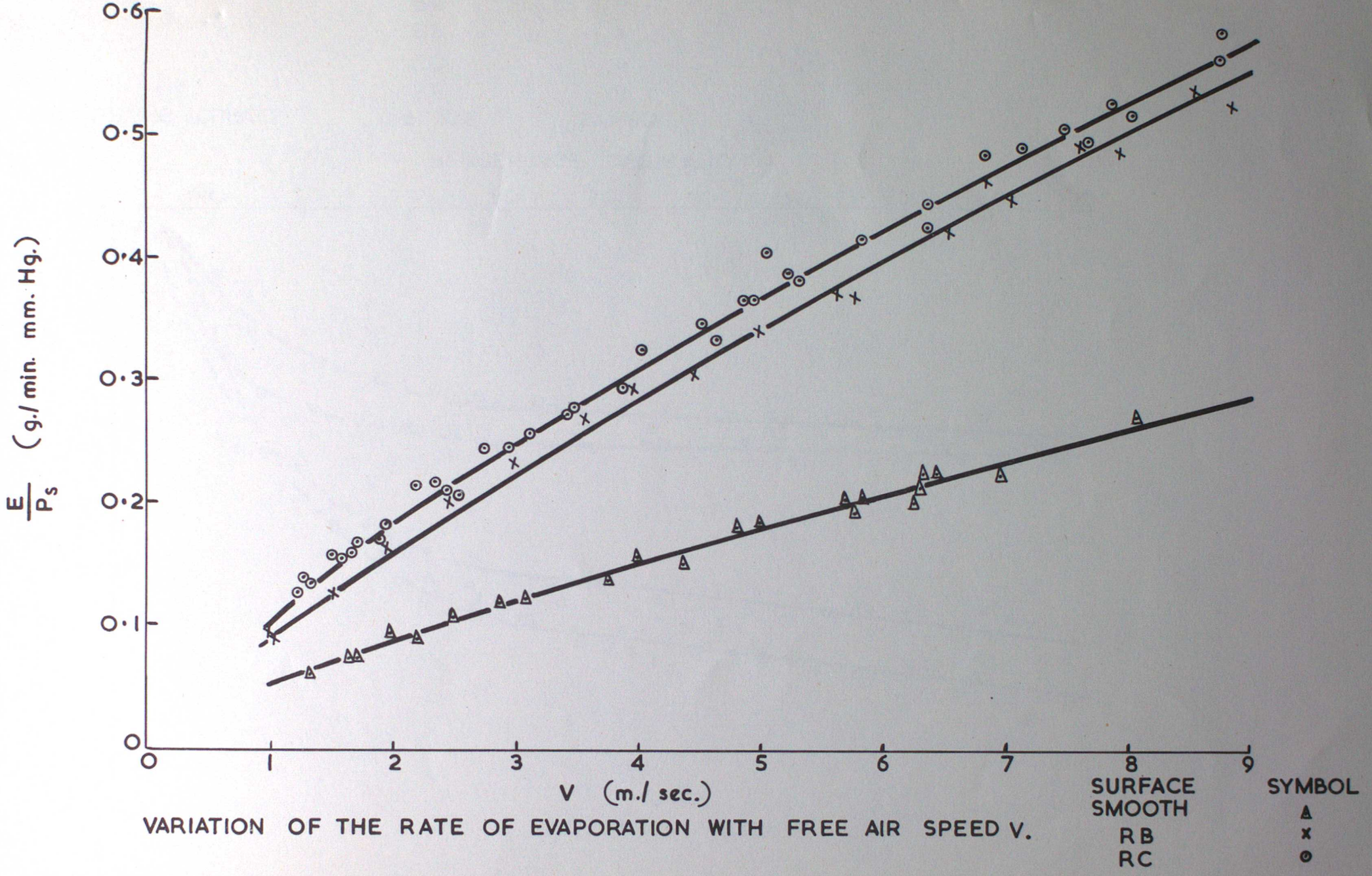

FIG. 4 VARIATION OF THE RATE OF EVAPORATION WITH FREE AIR SPEED V.

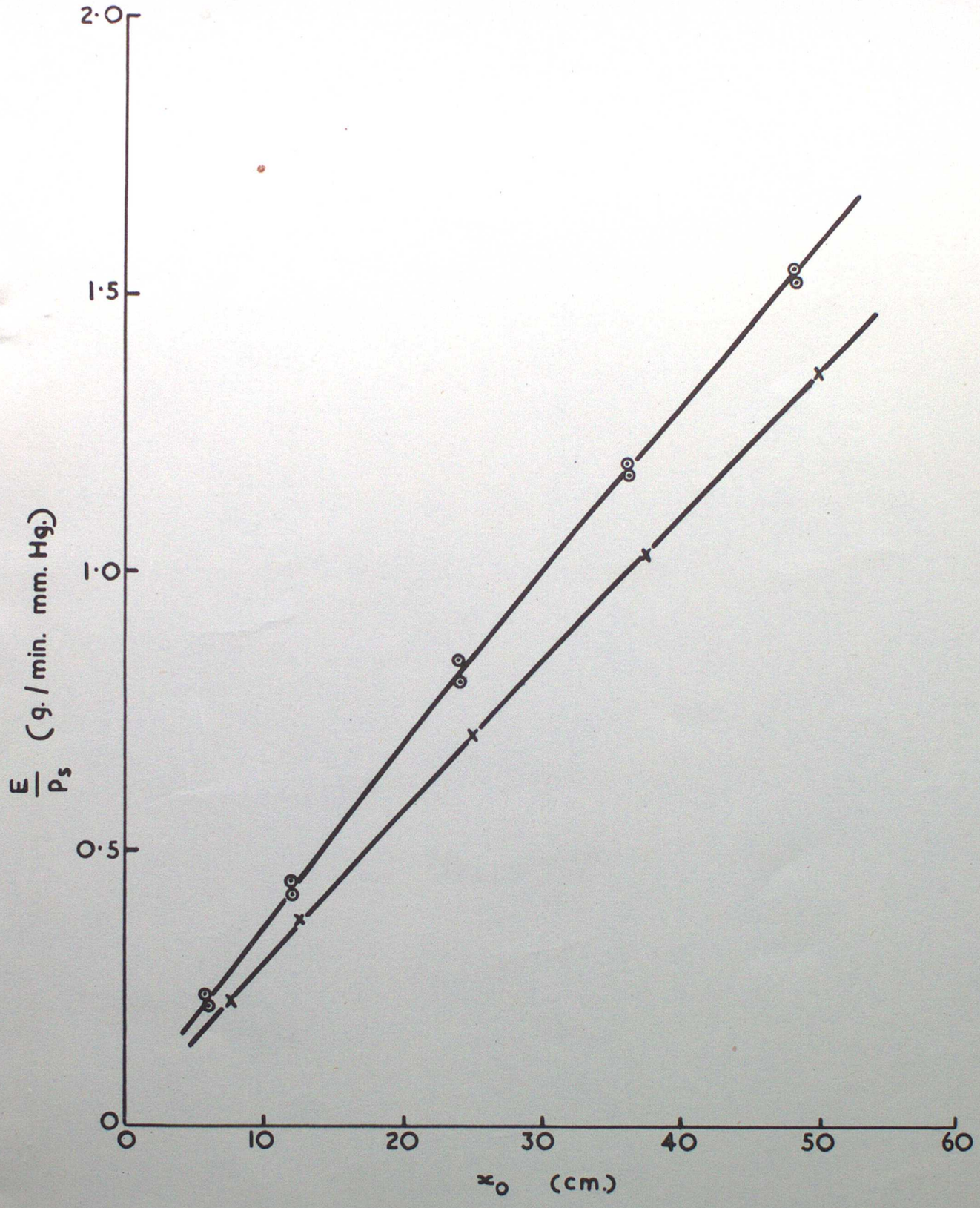

FIG. 5. VARIATION OF THE RATE OF EVAPORATION WITH DOWNWIND LENGTH x_0 OF SATURATED SURFACE.

SURFACE	SYMBOL
R B	×
R C	⊙